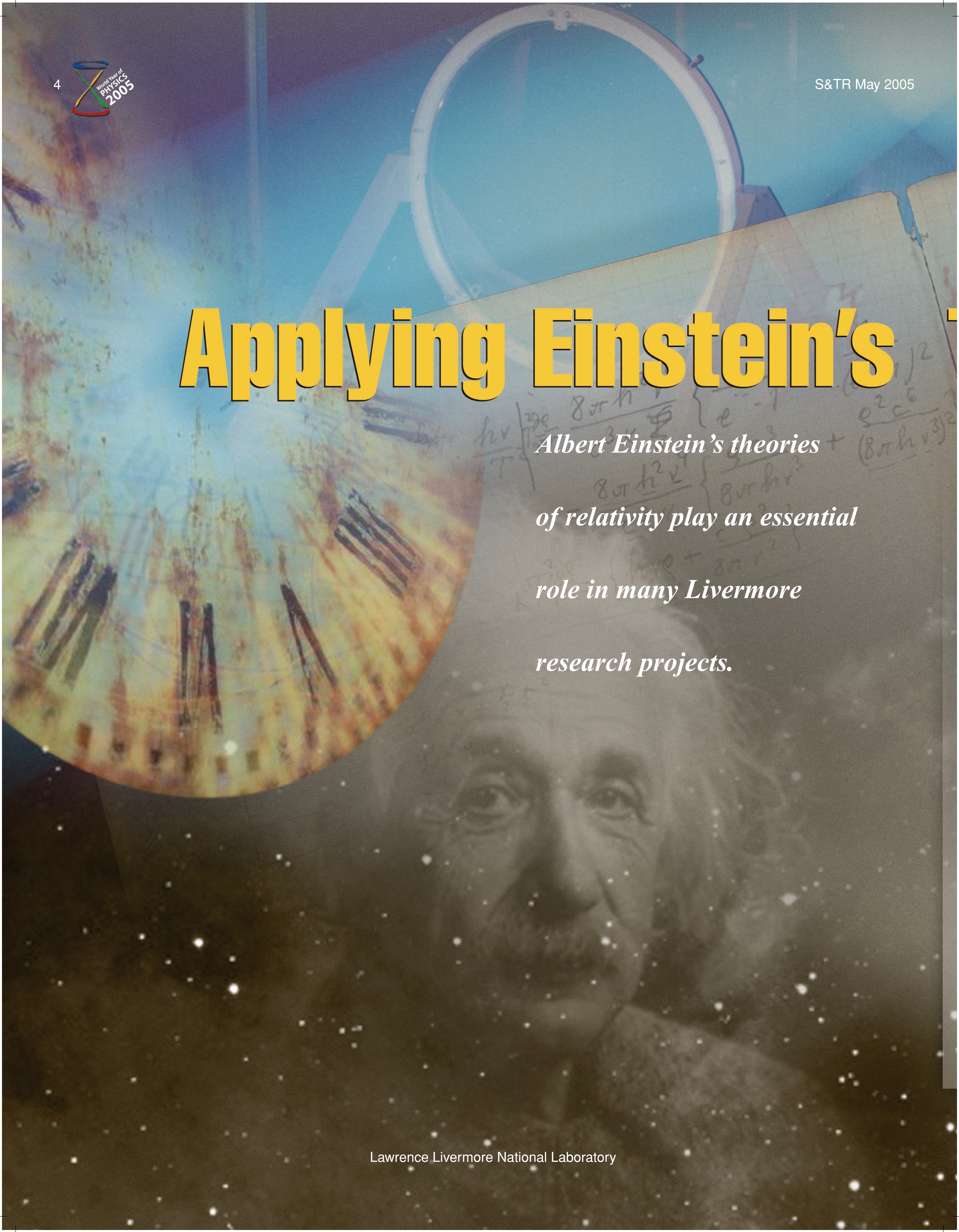


Applying Einstein's

Albert Einstein's theories of relativity play an essential role in many Livermore research projects.

Theories of Relativity

IN 1905, Albert Einstein wrote four papers that revolutionized the field of physics. The impact of his work helped launch quantum mechanics, deepened scientific knowledge about how molecules behave, and advanced understanding of astronomical objects and cosmology. Technologies such as solar power, global positioning systems, and digital equipment from computers to cameras stem from his insights into light, radiation, velocity, and gravity. Researchers at Lawrence Livermore and throughout the world continue to benefit from this legacy.

When he was a young man, Einstein is said to have asked himself what he would see if he could travel on a beam of light. He thought that if such an adventure were possible, he would see an oscillating electromagnetic field. In 1905, these reflections led Einstein to formulate what is now known as the theory of special relativity.

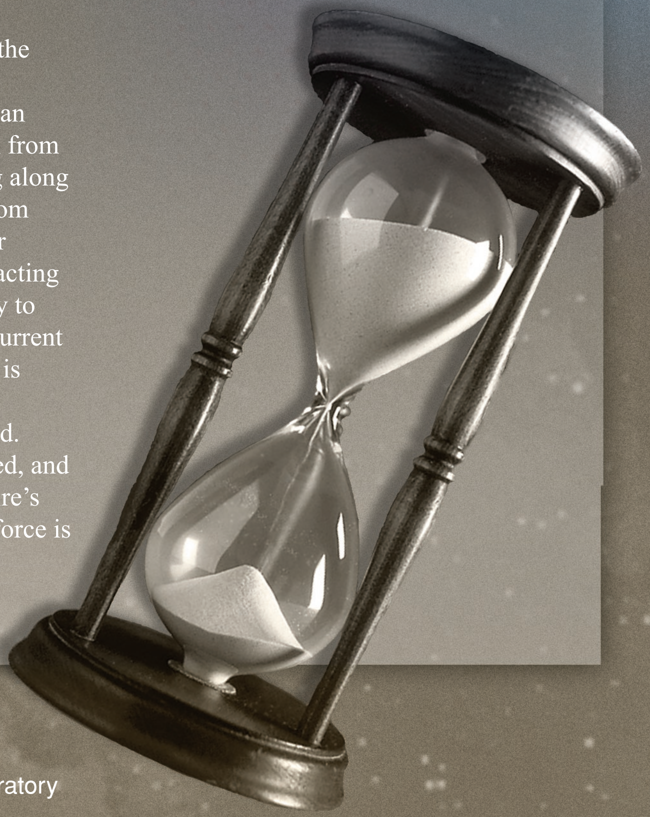
Light travels as a wave of oscillating electric and magnetic fields that are produced by the acceleration of electrically charged particles. In 1861, James Maxwell's research explained the relationship between electricity and magnetism. By the end of the 19th century, scientists discovered that all electromagnetic radiation travels at the same velocity—about 300,000 kilometers per second. This velocity is called the speed of light because light is a form of electromagnetic radiation, and it remains the same, regardless of the velocity of the emitting source or the receiver.

Speed of Light as a Constant

Because speed is the ratio of distance over time, Einstein reasoned that, if the speed of light is constant, measures of time and distance must vary from one observer to another, depending on their relative motion. Einstein wrote one of his 1905 papers, "On the Electrodynamics of Moving Bodies," to reconcile the difference in observed space and time between frames of reference with different velocities.

For example, the explanation for the force between a moving, electrically charged particle and a wire carrying an electrical current is different if given from the viewpoint of an observer moving along with the particle than it is if given from that of someone watching at rest. For someone watching at rest, the force acting on the moving particle is due entirely to the magnetic field produced by the current in the wire. But for an observer who is moving with the particle, no force is produced by the wire's magnetic field. Rather, the wire appears to be charged, and the force is caused entirely by the wire's electric field. The magnitude of the force is the same for both observers.

Einstein showed how to reconcile the disparity between the descriptions of observers moving and those at rest. Special relativity is based on two premises. First, light has the same speed for all observers regardless of their relative motion. Light velocity provides an upper limit for the speed of all forces, effects, and material objects. Second, the equations of physics are the same for observers moving at different relative speeds. A surprising consequence of these premises is that an observer's measurements of an object's characteristics—such as its size, mass,



and rate of time—depend on the relative velocity of the observer and the object. To an observer viewing an object as it approaches the speed of light, a clock traveling with the object appears to slow—almost to a stop—and the length of the object seems to shrink along the direction of travel.

Physicists categorize objects with velocities close to the speed of light as relativistic, and objects with velocities much less than the speed of light as nonrelativistic. Adding velocities is not as simple as mere arithmetic. For nonrelativistic speeds, the intuitive result is almost precisely correct. However, at relativistic speeds, it is not. For example, suppose an observer at rest sees a second observer traveling at a velocity of 0.8*c* (where *c* equals the speed of light). The second observer emits an object in the same direction and measures its speed as 0.7*c*. The first observer will not measure 1.5*c* as the object's speed. Because of the way in which velocities add according to special relativity, the observer will find 0.96*c* as the object's velocity.

Simulating the Big Bang

The relativistic change of mass and the apparent spatial length are important

In studies at Brookhaven National Laboratory's Relativistic Heavy-Ion Collider, gold ions accelerated to relativistic speeds appear flat rather than spherical.

factors in studies of matter in high-energy physics. For example, researchers are attempting to simulate the first microseconds after the big bang so they can explore new high-energy forms of matter and their origins. In a collaboration involving 40 institutions and 300 physicists from around the world, Livermore scientists are using the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory to accelerate gold ions to within 99.995 percent of the speed of light. (See *S&TR*, January/February 2003, pp. 4–9.) In RHIC, about 1 million ion collisions occur each second. Because a particle moving with extreme speed has much higher energy than a slow-moving particle, the nuclei shatter and are transformed into a plasma of their constituent quarks and gluons.

Scientists believe that quarks are the basic particles making up protons and neutrons. Additional particles called gluons mediate the strong force that holds quarks together and keeps the protons and neutrons in atomic nuclei. Quarks and gluons possess a type of charge called color, which is the source of the powerful forces that bind the quarks together. Quantum chromodynamics—the theory of the strong interaction, or color forces—states that quarks and gluons can be liberated only under high-temperature conditions similar to those in the very early universe. At that time, in the first moments of the big bang, quarks and gluons are free as part of a quark–gluon plasma.

The collisions between two nuclei at RHIC are highly explosive, releasing more than a trillion electronvolts of energy in a volume the size of an atomic nucleus. At these high speeds, a special relativistic effect, called Lorentz contraction, is noticeable. The nuclei appear flat rather than spherical. (See the figure at left.)

"Einstein's theory of special relativity is ingrained in the design of particle accelerators," says Livermore physicist Ron Soltz. "As the nuclei attain more energy, the velocity of the ions gets closer to the speed of light, but without ever reaching it. If we didn't have relativity, the way in which we use accelerators would be very different."

Soltz's team, which includes Livermore physicists Mike Heffner, Jennifer Klay, David Brown, and Ed Hartouni and postdoctoral researchers Jason Newby and Akitomo Enokizono, is running RHIC experiments with gold because the element has a heavy nucleus, from which it is easy to generate ions. The team has used lead, another element with a heavy nucleus. Next, they plan to experiment with copper, which has a lighter nucleus. Soltz explains, "The heavier the nucleus of an element is, the more particles there are to participate in the interaction. Because of our success with gold-to-gold collisions, we are trying a lighter element to determine if we will see similar plasma results."

Observing Celestial Fireworks

Einstein's theories on the speed of light and frames of reference also enable astrophysicists to understand celestial objects such as gamma-ray bursts (GRBs), supernovae, black holes, and neutron stars.

GRBs were discovered serendipitously in the late 1960s when U.S. military satellites were launched to ensure compliance with the Atmospheric Nuclear Test Ban Treaty. GRBs are short-lived, lasting from a few milliseconds to several minutes, and they release gamma-ray photons. The leading model to explain the events surrounding a GRB is the collapsing star, or collapsar, model. According to this model, a GRB arises when a dying, rotating star is too massive to successfully explode as a supernova. Instead, the iron core of the massive star collapses into a black hole surrounded by a dense accretion disk, thus emitting gamma rays with energies exceeding 100,000 electronvolts. (See *S&TR*, March 2005, pp. 24–26.)

Gamma rays are a very energetic part of the electromagnetic spectrum, which ranges from radio waves at the lowest energies through visible optical light at higher energies to gamma rays. The extreme energies released during GRBs make them the brightest source of gamma-ray photons in the observable universe, about a million trillion times as bright as the Sun. Gamma rays can be detected only from space because Earth's atmosphere absorbs them.

GRBs originate from deep space, some more than 8-billion light years away. They exhibit strong relativistic behaviors, including special relativistic aberration, in which light emitted is not uniformly distributed but rather is beamed to 1 percent of the sky in the direction of the jet's motion. From Earth, this emission appears as a jet of material that is ejected and accelerated to very nearly the speed of light. Because of relativistic effects, the jet's material moving directly toward an observer is seen to evolve more quickly than matter moving at an angle. Scientists refer to the directionality of a GRB's jet emission as relativistic beaming.

Only a few stars in a million produce GRBs when they die. On average, at least one GRB is observed every day somewhere in the universe. However, the number of events may be up to 500 times greater because only the GRBs that are beamed toward Earth can be observed. In November 2004, the National Aeronautics and Space Administration (NASA) launched the SWIFT telescope to conduct the most comprehensive study of GRBs to date.

Measuring a GRB's Afterglow

Researchers can predict a relationship between the brightness, temperature, and duration of a GRB by studying its jet. Following the release of gamma rays, the ejected material continues to move away from the exploding collapsar and, like a snowplow, gathers material from interstellar space. As the energetic shell sweeps up material, it slows down and cools, emitting progressively lower energies of the electromagnetic spectrum, from x rays through radio waves. This effect, called the afterglow, fades over time, lasting from a few days to several years. However, because the afterglow lasts substantially longer than the GRB, astrophysicists can study it to glean information about the nature of the surrounding environment.

Livermore astrophysicist Jay Salmonson says, "One feature we look for is how the material cools in a burst. As material cools, it forms a light curve with a characteristic decay slope. At some point, the curve breaks and becomes steeper. This change indicates that the shock is slowing, and beaming becomes less pronounced. We can then see more of the shock area, which allows us to determine the jet's size and energy as well as what caused it."

Salmonson has developed a model to study possible afterglow shapes at various viewing angles. Called AfterglowView, the program calculates what an observer at a specific orientation relative to the jet's axis would see from a GRB. By comparing predictions with observations, his team hopes to gain clues as to the shape and size of afterglows. The studies require detailed accounting of relativistic motions of material through space–time. Salmonson says, "So far, we've inferred the angular size of a jet to be 5 to 10 degrees. One surprising result of our studies is that most bursts appear to have the same amount of energy, although they presumably originated from a range of stellar progenitors."

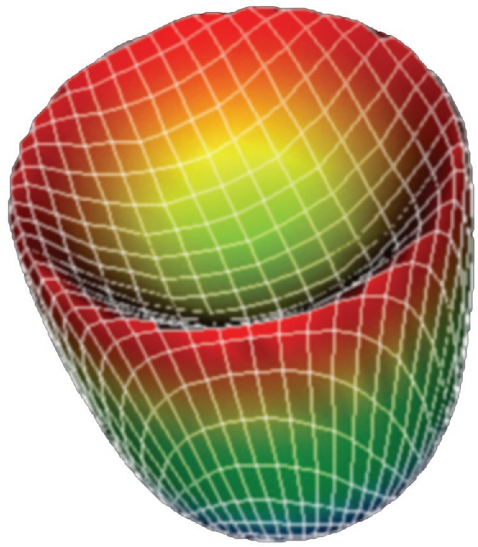
Adding Gravity to the Equation

In 1907, Einstein began work on an extension to special relativity. Called the theory of general relativity, it described gravitation and its relation to the other forces of nature.

Isaac Newton's theory of gravitation states that masses experience an attractive force between them. This force, which acts at a distance, accelerates masses toward each other. The strength of the force depends on the size of the masses and is inversely proportional to the square of the distance between them. In Newton's universe, space existed independent of the matter contained within it.

Newtonian physics explains how to calculate forces that are caused by the mass of a body, but it does not explain why matter causes gravity. Einstein proposed that matter bent space and time, and this distortion is what is perceived as gravity. The more massive an object is in space, the larger the space and time distortion around it and, hence, the stronger its gravity.

The theory of general relativity states that bodies, regardless of their mass, fall freely in a uniform gravitational field with the same acceleration. Thus, the effects of gravity are equivalent to the effect of an accelerated frame of reference without gravity. Einstein proposed that, without a frame of reference, no one can distinguish



This three-dimensional model shows the surface of an afterglow as viewed from Earth. Brighter areas of the afterglow are red, and dimmer areas are blue.

between acceleration and gravitation. This idea is known as the principle of equivalence. Several predictions result from this theory: that light and all forms of electromagnetic radiation are deflected or bent by gravitational force, that a clock on the surface of a massive object will run slower than a clock in open space, and that gravitational waves radiate at the speed of light from large masses that are accelerating.

Codes to Model the Universe

With Einstein's theories of special and general relativity, researchers can model the forces in the universe to study its origins, determine how celestial objects influence one another, and then predict the evolution of these objects. Unfortunately, the equations of general relativity are complex and difficult to solve. Advances in computing methods and technologies have been essential to understanding cosmological models, the universe, and astrophysical processes within them, by allowing researchers to solve the relativistic equations on computers.

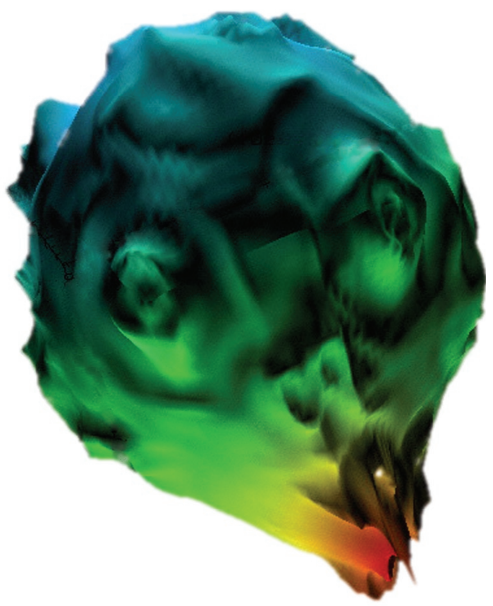
In 1968, Laboratory physicist Jim Wilson began work in numerical relativity, which explores the computational aspects of general relativity and its applications for cosmology, astrophysics, and gravitational-wave physics. Beginning with one-dimensional codes and later working with two- and three-dimensional codes, Wilson applied Einstein's complex, nonlinear partial differential equations to advance understanding in astrophysics. Over the last three decades, he has developed several codes that work on Livermore's supercomputers to model a variety of phenomena. His research has explored heavy-ion collisions, supernova explosions, black-hole accretion and encounters, energy extraction from magnetic black holes, black-hole formation in neutron-star binaries, thermonuclear initiation from white dwarfs, and GRB production in neutron-star binaries.

Wilson is collaborating with Livermore physicist Dave Dearborn and Grant Matthews from the University of Notre Dame to study how stars are destroyed by a black hole at the center of the galaxy. Their research indicates that stars known as white dwarfs become unstable when they are subjected to the strong gravitational field near a black hole. If a white dwarf passes too closely to a black hole, carbon and oxygen in the star's center are squeezed, initiating a runaway thermonuclear burn that blows the star apart. To better understand these phenomena, Wilson and his collaborators are modeling such events using both a general relativity code and the Djehuty stellar evolution code. (See *S&TR*, May 2002, pp. 4–10.)

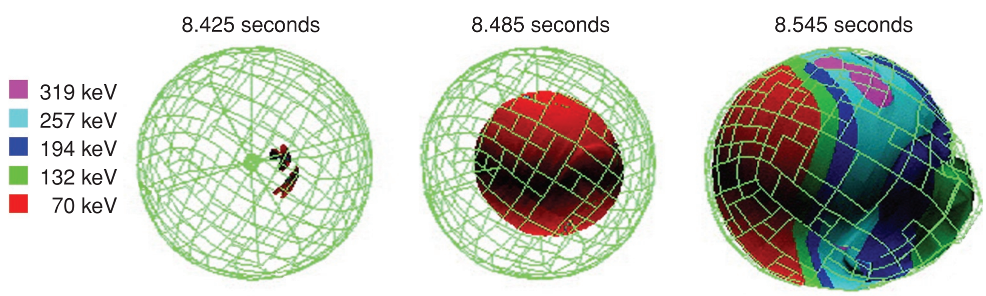
Modeling Whirling Black Holes

The application of numerical relativity is being continued in the COSMOS code. In 2001, Livermore astrophysicist Peter Anninos completed the code, which can calculate relativistic problems. One of the first applications of COSMOS was to model astrophysical events having special relativistic effects, such as first-order cosmological phase transitions occurring in the first fractions of a second after the big bang. These simulations allowed researchers to investigate the stability of quark–hadron phase boundaries and the possibility of generating primordial perturbations in hadronic matter that could grow to become galaxies. (See *S&TR*, March 2003, pp. 4–11.)

In 2004, Anninos added magnetic fields and adaptive, or moving, meshes to the COSMOS code. He and astrophysicist Chris Fragile began modeling astrophysical events for which general relativistic effects are significant. The mesh enhancement allows the team to follow the way gas flows behave near black holes—in particular, the pancake-shaped distribution of matter outside a black hole known as an accretion disk. The team models such characteristics as black-hole spin and the



This simulation of the supernova stage of a white dwarf shows the range in speed from various areas of the exploding mass, from 5,000 kilometers per second (blue) to 74,000 kilometers per second (orange).



As the supernova remnants move outward, the regions vary in temperature. This simulation shows a range from 70 to 319 kiloelectronvolts (keV; 1 keV is equivalent to 11 million kelvins.)

tilt and sound speed of the accretion disk to determine the range of possible effects, including the relativistic effect known as frame dragging.

Any object with mass warps the space and time around it, but a rotating object distorts space–time more radically, twisting it like a pinwheel around the object. Earth's rotation is sufficient to cause satellites to be dragged by 2 meters every year. Near a spinning black hole, frame dragging changes the shape of the accretion disk and affects how much gas can be captured by the black hole.

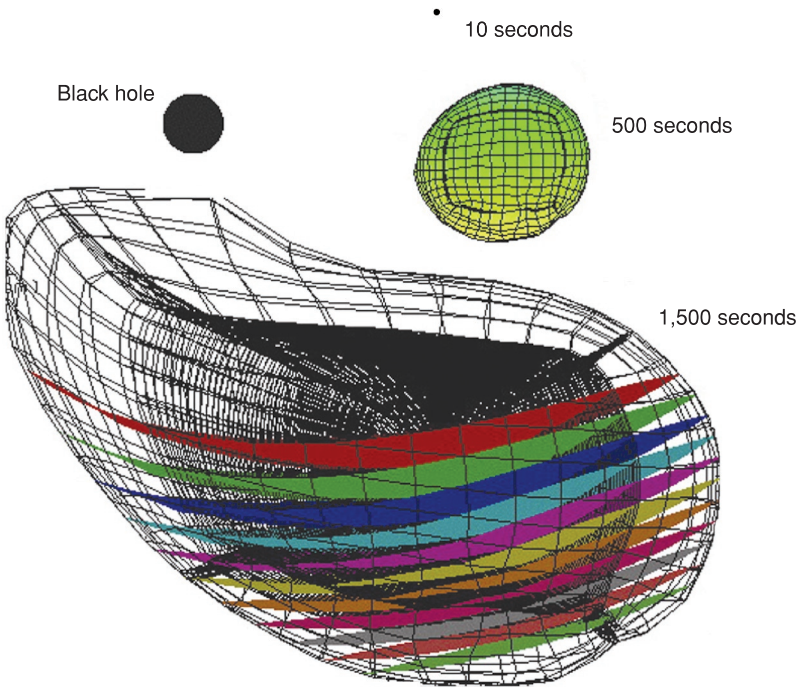
Livermore is the first to simulate frame-dragging effects on generic gas flows with no assumed space–time symmetries. The team is also simulating GRB systems, black hole–neutron star binaries, and magnetized jet outflows from black-hole accretion disks. The researchers have examined tilted disks around rapidly rotating black holes and are now including magnetic fields in the simulations. They also are exploring oscillation modes in black-hole accretion disks. Astronomers have observed periodic oscillations in the x-ray light curves of accreting black holes. One possible explanation is that the accretion disk, which emits x rays, is oscillating, producing an effect similar to sounding a note on a musical instrument.

A Place Light Can't Escape

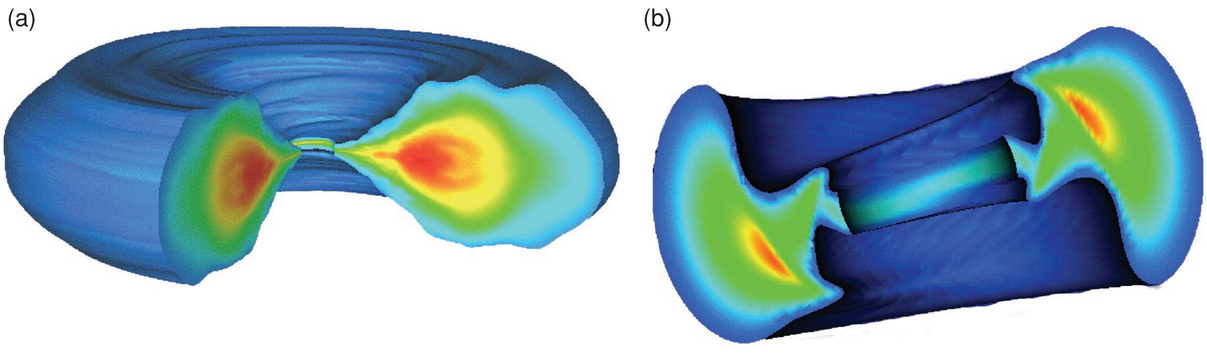
The greater the mass of an object, the stronger is its gravitational pull. If a star is sufficiently massive, its gravitational pull crushes atoms. Electrons combine with protons in the atomic nuclei to form neutrons. The nuclei are crushed together, which reduces the star to a huge conglomeration of neutrons, called a neutron star.

Perhaps the most extraordinary prediction of general relativity is that sometimes a neutron star becomes a black hole. A black hole is a mass so concentrated, and thus its gravitational hold so powerful, that an object's velocity would have to exceed the speed of light to escape the hole's surface, or event horizon.

Black holes are described by two parameters: mass and angular momentum.



A simulation shows the evolution of a white dwarf after it explodes and nears the gravitational pull of a black hole. Each color represents a different energy level, and the color bands represent supernova remnants that have enough energy to escape the black hole's gravitational pull. The black region above the bands represents supernova remnants that either will be pulled into the black hole or will orbit it, forming an accretion disk.



(a) This snapshot from a three-dimensional simulation shows gas in an accretion disk and within a magnetic field, orbiting a black hole. (b) In another view, the gas is in a tilting accretion disk that orbits a rapidly rotating black hole.

Scientists determine these parameters by studying the region surrounding the event horizon and knowing the stellar progenitor of a black hole. When a spinning neutron star collapses into a black hole, the hole also spins to conserve angular momentum. In 1916, Karl Schwarschild solved gravitational field equations for a nonspinning black hole, but it was not until 1963 that Roy Kerr discovered a solution for a spinning black hole.

Although a black hole emits no light, matter from nearby stars can be captured by its gravitational field, creating an accretion disk. Matter in the disk gradually spirals inward, converting gravitational potential energy into kinetic energy, thermal energy, and light. As this matter approaches the event horizon, it reaches relativistic velocities. Because black holes have a small angular size, or observational angle, scientists cannot yet image these environments directly. Instead, they study the radiation emitted from a black hole's accretion disk, much of which emerges as x rays.

Measuring Relativistic Effects

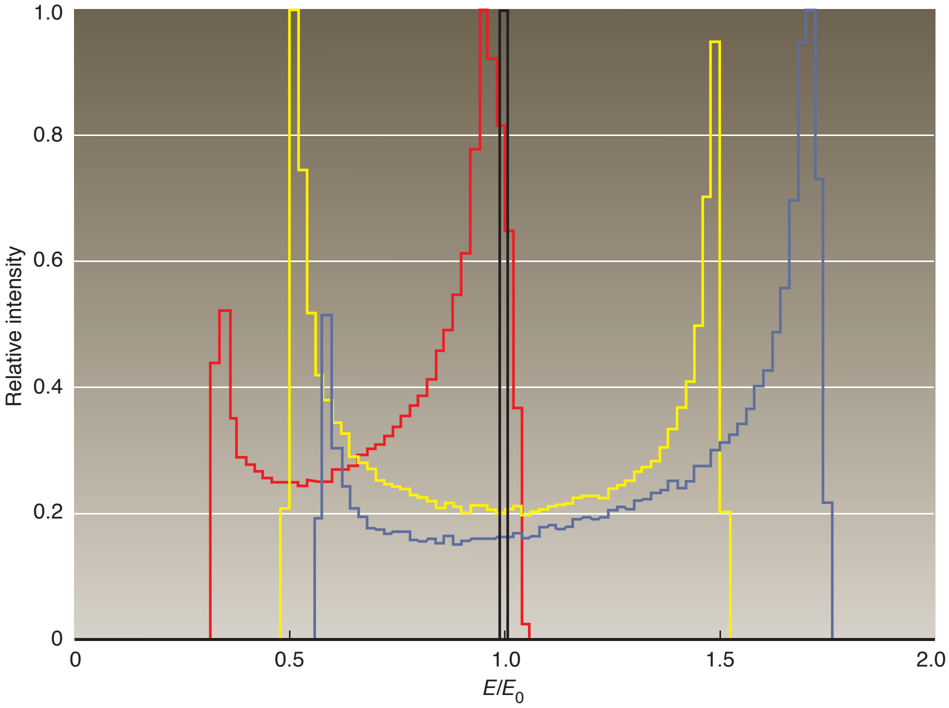
In collaboration with researchers at the Massachusetts Institute of Technology and the Harvard-Smithsonian Center for Astrophysics, Laboratory astrophysicists Duane Liedahl and Christopher Mauche are developing computer codes to model the complex physics associated with x-ray spectral emission from an accreting black hole.

The COMPASS code (computer models of the physics of accretion disk structure and spectra) was developed by the collaborative group in the 1990s. It can model the temperature, density, ionization state, and velocity of matter in the accretion disk. COMPASS incorporates HULLAC (Hebrew University and Lawrence Livermore atomic code), a code originally developed in the 1980s. HULLAC generates atomic models to determine the heating and cooling of the accretion disk and the spectrum of the emitted light. A Monte Carlo–based photon propagator has also been developed to track individual photons during their path through space–time.

Accretion disks are made up of common elements such as hydrogen, helium, oxygen, and iron. These elements are ionized by the photoelectric effect, which results when an ion absorbs a high-energy photon and, in turn, ejects an electron. Left in a state of high excitation, the ion can return to its lowest energy level by emitting a photon, which for iron has an energy of 6.4 kiloelectronvolts. In the x-ray spectrum, this energy normally appears as a narrow line on top of a radiation continuum. However, for a black-hole accretion disk, the lines are highly distorted by several classical and relativistic effects.

One such effect, called the Doppler effect, accounts for the change in the frequency of electromagnetic waves as an object moves toward or away from an observer. The Doppler effect alters the energy or color of light. For example, light from a star moving toward an observer appears bluer, but light from a star moving away from the observer appears redder.

In an accretion disk, the Doppler effect broadens iron's narrow energy line into a



As matter in an accretion disk orbits a black hole, relativistic effects occur. The intrinsic energy of an iron line is represented by the narrow spike (black) at E/E_0, where E is energy and E_0 is energy with no effects. The high-rotation velocity of disk material near a black hole broadens the iron spike into a double-horned profile (yellow). The relativistic Doppler effect and relativistic aberration also cause the profile to shift (blue). Finally, as photons climb out of the gravitational well surrounding a black hole, they lose energy, resulting in a gravitational redshift (red).

double-horned profile, which for the high velocities (150,000 kilometers per second or half the speed of light) near a black hole, extends from 0.5 to 1.5 times the original energy of the line. Relativistic effects, such as time dilation and the beaming of the radiation in the direction of motion, further distort the line, dimming the red horn of the profile and brightening the blue horn. Finally, the emitted photons lose a significant fraction of their energy as they climb out of the gravitational well that surrounds a black hole, leading to a net redshift of the line profile. The resulting broad, skewed, and redshifted lines observed from Earth are the unmistakable signature of black-hole accretion disks.

Liedahl and Mauche's computer models account for all these effects, allowing the team to calculate x-ray spectra as a function of black-hole spin and the angle of observation. These data are then compared to spectra collected from satellites such as NASA's Chandra X-Ray Observatory and the European Space Agency's XMM-Newton. X-ray satellites to be deployed in the next decade, such as NASA's Constellation-X Observatory, are expected to provide about 100 times the sensitivity of current satellites, allowing scientists to study in even more detail the extreme environments surrounding accreting black holes.

Bewildering But Essential

To many, Einstein's theories of special and general relativity seem bewildering and violate common sense. However, to scientists, the theories are essential to understanding the universe. Einstein began by wondering what he would see if he traveled on a beam of light. One hundred years later, many researchers, including those at Livermore, are applying his theories to accelerate particles to almost the speed of light, model various astronomical and cosmological events, and gain insight into mathematical and physics properties to help in areas such as stockpile stewardship. Einstein left a rich legacy from that miracle year of physics in 1905, and his legacy continues to influence physics research to this day.

—Gabriele Rennie

Key Words: AfterglowView, Albert Einstein, COMPASS (computer models of the physics of accretion disk structure and spectra) code, COSMOS code, HULLAC (Hebrew University and Lawrence Livermore atomic code), Relativistic Heavy-Ion Collider (RHIC), speed of light, theory of general relativity, theory of special relativity.

For information on Lawrence Livermore's activities for the World Year of Physics, see www.llnl.gov/pao/WYOP.

Albert Einstein in Santa Barbara, 1933. (Reprinted courtesy of the Archives, California Institute of Technology, and the Albert Einstein Archives, the Jewish National and University Library, the Hebrew University of Jerusalem, Israel.)